

# Search for Prompt Production of $\chi_c$ and $X(3872)$ in $e^+e^-$ Annihilations

B. Aubert,<sup>1</sup> M. Bona,<sup>1</sup> D. Boutigny,<sup>1</sup> Y. Karyotakis,<sup>1</sup> J. P. Lees,<sup>1</sup> V. Poireau,<sup>1</sup> X. Prudent,<sup>1</sup> V. Tisserand,<sup>1</sup>  
A. Zghiche,<sup>1</sup> J. Garra Tico,<sup>2</sup> E. Grauges,<sup>2</sup> L. Lopez,<sup>3</sup> A. Palano,<sup>3</sup> G. Eigen,<sup>4</sup> B. Stugu,<sup>4</sup> L. Sun,<sup>4</sup> G. S. Abrams,<sup>5</sup>  
M. Battaglia,<sup>5</sup> D. N. Brown,<sup>5</sup> J. Button-Shafer,<sup>5</sup> R. N. Cahn,<sup>5</sup> Y. Groysman,<sup>5</sup> R. G. Jacobsen,<sup>5</sup> J. A. Kadyk,<sup>5</sup>  
L. T. Kerth,<sup>5</sup> Yu. G. Kolomensky,<sup>5</sup> G. Kukartsev,<sup>5</sup> D. Lopes Pegna,<sup>5</sup> G. Lynch,<sup>5</sup> L. M. Mir,<sup>5</sup> T. J. Orimoto,<sup>5</sup>  
M. T. Ronan,<sup>5,\*</sup> K. Tackmann,<sup>5</sup> W. A. Wenzel,<sup>5</sup> P. del Amo Sanchez,<sup>6</sup> C. M. Hawkes,<sup>6</sup> A. T. Watson,<sup>6</sup>  
T. Held,<sup>7</sup> H. Koch,<sup>7</sup> B. Lewandowski,<sup>7</sup> M. Pelizaeus,<sup>7</sup> T. Schroeder,<sup>7</sup> M. Steinke,<sup>7</sup> D. Walker,<sup>8</sup> D. J. Asgeirsson,<sup>9</sup>  
T. Cuhadar-Donszelmann,<sup>9</sup> B. G. Fulsom,<sup>9</sup> C. Hearty,<sup>9</sup> T. S. Mattison,<sup>9</sup> J. A. McKenna,<sup>9</sup> A. Khan,<sup>10</sup> M. Saleem,<sup>10</sup>  
L. Teodorescu,<sup>10</sup> V. E. Blinov,<sup>11</sup> A. D. Bukin,<sup>11</sup> V. P. Druzhinin,<sup>11</sup> V. B. Golubev,<sup>11</sup> A. P. Onuchin,<sup>11</sup>  
S. I. Serednyakov,<sup>11</sup> Yu. I. Skovpen,<sup>11</sup> E. P. Solodov,<sup>11</sup> K. Yu. Todyshev,<sup>11</sup> M. Bondioli,<sup>12</sup> S. Curry,<sup>12</sup> I. Eschrich,<sup>12</sup>  
D. Kirkby,<sup>12</sup> A. J. Lankford,<sup>12</sup> P. Lund,<sup>12</sup> M. Mandelkern,<sup>12</sup> E. C. Martin,<sup>12</sup> D. P. Stoker,<sup>12</sup> S. Abachi,<sup>13</sup>  
C. Buchanan,<sup>13</sup> S. D. Foulkes,<sup>14</sup> J. W. Gary,<sup>14</sup> F. Liu,<sup>14</sup> O. Long,<sup>14</sup> B. C. Shen,<sup>14</sup> L. Zhang,<sup>14</sup> H. P. Paar,<sup>15</sup>  
S. Rahatlou,<sup>15</sup> V. Sharma,<sup>15</sup> J. W. Berryhill,<sup>16</sup> C. Campagnari,<sup>16</sup> A. Cunha,<sup>16</sup> B. Dahmes,<sup>16</sup> T. M. Hong,<sup>16</sup>  
D. Kovalskiy,<sup>16</sup> J. D. Richman,<sup>16</sup> T. W. Beck,<sup>17</sup> A. M. Eisner,<sup>17</sup> C. J. Flacco,<sup>17</sup> C. A. Heusch,<sup>17</sup> J. Kroseberg,<sup>17</sup>  
W. S. Lockman,<sup>17</sup> T. Schalk,<sup>17</sup> B. A. Schumm,<sup>17</sup> A. Seiden,<sup>17</sup> D. C. Williams,<sup>17</sup> M. G. Wilson,<sup>17</sup> L. O. Winstrom,<sup>17</sup>  
E. Chen,<sup>18</sup> C. H. Cheng,<sup>18</sup> F. Fang,<sup>18</sup> D. G. Hitlin,<sup>18</sup> I. Narsky,<sup>18</sup> T. Piatenko,<sup>18</sup> F. C. Porter,<sup>18</sup> R. Andreassen,<sup>19</sup>  
G. Mancinelli,<sup>19</sup> B. T. Meadows,<sup>19</sup> K. Mishra,<sup>19</sup> M. D. Sokoloff,<sup>19</sup> F. Blanc,<sup>20</sup> P. C. Bloom,<sup>20</sup> S. Chen,<sup>20</sup>  
W. T. Ford,<sup>20</sup> J. F. Hirschauer,<sup>20</sup> A. Kreisel,<sup>20</sup> M. Nagel,<sup>20</sup> U. Nauenberg,<sup>20</sup> A. Olivas,<sup>20</sup> J. G. Smith,<sup>20</sup>  
K. A. Ulmer,<sup>20</sup> S. R. Wagner,<sup>20</sup> J. Zhang,<sup>20</sup> A. M. Gabareen,<sup>21</sup> A. Soffer,<sup>21</sup> W. H. Toki,<sup>21</sup> R. J. Wilson,<sup>21</sup>  
F. Winklmeier,<sup>21</sup> Q. Zeng,<sup>21</sup> D. D. Altenburg,<sup>22</sup> E. Feltresi,<sup>22</sup> A. Hauke,<sup>22</sup> H. Jasper,<sup>22</sup> J. Merkel,<sup>22</sup> A. Petzold,<sup>22</sup>  
B. Spaan,<sup>22</sup> K. Wacker,<sup>22</sup> T. Brandt,<sup>23</sup> V. Klose,<sup>23</sup> M. J. Kobel,<sup>23</sup> H. M. Lacker,<sup>23</sup> W. F. Mader,<sup>23</sup> R. Nogowski,<sup>23</sup>  
J. Schubert,<sup>23</sup> K. R. Schubert,<sup>23</sup> R. Schwierz,<sup>23</sup> J. E. Sundermann,<sup>23</sup> A. Volk,<sup>23</sup> D. Bernard,<sup>24</sup> G. R. Bonneaud,<sup>24</sup>  
E. Latour,<sup>24</sup> V. Lombardo,<sup>24</sup> Ch. Thiebaux,<sup>24</sup> M. Verderi,<sup>24</sup> P. J. Clark,<sup>25</sup> W. Gradl,<sup>25</sup> F. Muheim,<sup>25</sup> S. Playfer,<sup>25</sup>  
A. I. Robertson,<sup>25</sup> Y. Xie,<sup>25</sup> M. Andreotti,<sup>26</sup> D. Bettoni,<sup>26</sup> C. Bozzi,<sup>26</sup> R. Calabrese,<sup>26</sup> A. Cecchi,<sup>26</sup> G. Cibinetto,<sup>26</sup>  
P. Franchini,<sup>26</sup> E. Luppi,<sup>26</sup> M. Negrini,<sup>26</sup> A. Petrella,<sup>26</sup> L. Piemontese,<sup>26</sup> E. Prencipe,<sup>26</sup> V. Santoro,<sup>26</sup> F. Anulli,<sup>27</sup>  
R. Baldini-Ferroli,<sup>27</sup> A. Calcaterra,<sup>27</sup> R. de Sangro,<sup>27</sup> G. Finocchiaro,<sup>27</sup> S. Pacetti,<sup>27</sup> P. Patteri,<sup>27</sup> I. M. Peruzzi,<sup>27,†</sup>  
M. Piccolo,<sup>27</sup> M. Rama,<sup>27</sup> A. Zallo,<sup>27</sup> A. Buzzo,<sup>28</sup> R. Contri,<sup>28</sup> M. Lo Vetere,<sup>28</sup> M. M. Macri,<sup>28</sup> M. R. Monge,<sup>28</sup>  
S. Passaggio,<sup>28</sup> C. Patrignani,<sup>28</sup> E. Robutti,<sup>28</sup> A. Santroni,<sup>28</sup> S. Tosi,<sup>28</sup> K. S. Chaisanguanthum,<sup>29</sup> M. Morii,<sup>29</sup>  
J. Wu,<sup>29</sup> R. S. Dubitzky,<sup>30</sup> J. Marks,<sup>30</sup> S. Schenk,<sup>30</sup> U. Uwer,<sup>30</sup> D. J. Bard,<sup>31</sup> P. D. Dauncey,<sup>31</sup> R. L. Flack,<sup>31</sup>  
J. A. Nash,<sup>31</sup> M. B. Nikolich,<sup>31</sup> W. Panduro Vazquez,<sup>31</sup> M. Tibbetts,<sup>31</sup> P. K. Behera,<sup>32</sup> X. Chai,<sup>32</sup>  
M. J. Charles,<sup>32</sup> U. Mallik,<sup>32</sup> N. T. Meyer,<sup>32</sup> V. Ziegler,<sup>32</sup> J. Cochran,<sup>33</sup> H. B. Crawley,<sup>33</sup> L. Dong,<sup>33</sup> V. Eyges,<sup>33</sup>  
W. T. Meyer,<sup>33</sup> S. Prell,<sup>33</sup> E. I. Rosenberg,<sup>33</sup> A. E. Rubin,<sup>33</sup> A. V. Gritsan,<sup>34</sup> Z. J. Guo,<sup>34</sup> C. K. Lae,<sup>34</sup>  
A. G. Denig,<sup>35</sup> M. Fritsch,<sup>35</sup> G. Schott,<sup>35</sup> N. Arnaud,<sup>36</sup> J. Béquilleux,<sup>36</sup> M. Davier,<sup>36</sup> G. Grosdidier,<sup>36</sup> A. Höcker,<sup>36</sup>  
V. Lepeltier,<sup>36</sup> F. Le Diberder,<sup>36</sup> A. M. Lutz,<sup>36</sup> S. Pruvot,<sup>36</sup> S. Rodier,<sup>36</sup> P. Roudeau,<sup>36</sup> M. H. Schune,<sup>36</sup>  
J. Serrano,<sup>36</sup> V. Sordini,<sup>36</sup> A. Stocchi,<sup>36</sup> W. F. Wang,<sup>36</sup> G. Wormser,<sup>36</sup> D. J. Lange,<sup>37</sup> D. M. Wright,<sup>37</sup>  
I. Bingham,<sup>38</sup> C. A. Chavez,<sup>38</sup> I. J. Forster,<sup>38</sup> J. R. Fry,<sup>38</sup> E. Gabathuler,<sup>38</sup> R. Gamet,<sup>38</sup> D. E. Hutchcroft,<sup>38</sup>  
D. J. Payne,<sup>38</sup> K. C. Schofield,<sup>38</sup> C. Touramanis,<sup>38</sup> A. J. Bevan,<sup>39</sup> K. A. George,<sup>39</sup> F. Di Lodovico,<sup>39</sup> W. Menges,<sup>39</sup>  
R. Sacco,<sup>39</sup> G. Cowan,<sup>40</sup> H. U. Flaecher,<sup>40</sup> D. A. Hopkins,<sup>40</sup> S. Paramesvaran,<sup>40</sup> F. Salvatore,<sup>40</sup> A. C. Wren,<sup>40</sup>  
D. N. Brown,<sup>41</sup> C. L. Davis,<sup>41</sup> J. Allison,<sup>42</sup> N. R. Barlow,<sup>42</sup> R. J. Barlow,<sup>42</sup> Y. M. Chia,<sup>42</sup> C. L. Edgar,<sup>42</sup>  
G. D. Lafferty,<sup>42</sup> T. J. West,<sup>42</sup> J. I. Yi,<sup>42</sup> J. Anderson,<sup>43</sup> C. Chen,<sup>43</sup> A. Jawahery,<sup>43</sup> D. A. Roberts,<sup>43</sup> G. Simi,<sup>43</sup>  
J. M. Tuggle,<sup>43</sup> G. Blaylock,<sup>44</sup> C. Dallapiccola,<sup>44</sup> S. S. Hertzbach,<sup>44</sup> X. Li,<sup>44</sup> T. B. Moore,<sup>44</sup> E. Salvati,<sup>44</sup>  
S. Saremi,<sup>44</sup> R. Cowan,<sup>45</sup> D. Dujmic,<sup>45</sup> P. H. Fisher,<sup>45</sup> K. Koeneke,<sup>45</sup> G. Sciolla,<sup>45</sup> S. J. Sekula,<sup>45</sup> M. Spitznagel,<sup>45</sup>  
F. Taylor,<sup>45</sup> R. K. Yamamoto,<sup>45</sup> M. Zhao,<sup>45</sup> Y. Zheng,<sup>45</sup> S. E. Mclachlin,<sup>46</sup> P. M. Patel,<sup>46</sup> S. H. Robertson,<sup>46</sup>  
A. Lazzaro,<sup>47</sup> F. Palombo,<sup>47</sup> J. M. Bauer,<sup>48</sup> L. Cremaldi,<sup>48</sup> V. Eschenburg,<sup>48</sup> R. Godang,<sup>48</sup> R. Kroeger,<sup>48</sup>  
D. A. Sanders,<sup>48</sup> D. J. Summers,<sup>48</sup> H. W. Zhao,<sup>48</sup> S. Brunet,<sup>49</sup> D. Côté,<sup>49</sup> M. Simard,<sup>49</sup> P. Taras,<sup>49</sup>  
F. B. Viaud,<sup>49</sup> H. Nicholson,<sup>50</sup> G. De Nardo,<sup>51</sup> F. Fabozzi,<sup>51,‡</sup> L. Lista,<sup>51</sup> D. Monorchio,<sup>51</sup> C. Sciacca,<sup>51</sup>

M. A. Baak,<sup>52</sup> G. Raven,<sup>52</sup> H. L. Snoek,<sup>52</sup> C. P. Jessop,<sup>53</sup> J. M. LoSecco,<sup>53</sup> G. Benelli,<sup>54</sup> L. A. Corwin,<sup>54</sup> K. Honscheid,<sup>54</sup> H. Kagan,<sup>54</sup> R. Kass,<sup>54</sup> J. P. Morris,<sup>54</sup> A. M. Rahimi,<sup>54</sup> J. J. Regensburger,<sup>54</sup> Q. K. Wong,<sup>54</sup> N. L. Blount,<sup>55</sup> J. Brau,<sup>55</sup> R. Frey,<sup>55</sup> O. Igonkina,<sup>55</sup> J. A. Kolb,<sup>55</sup> M. Lu,<sup>55</sup> R. Rahmat,<sup>55</sup> N. B. Sinev,<sup>55</sup> D. Strom,<sup>55</sup> J. Strube,<sup>55</sup> E. Torrence,<sup>55</sup> N. Gagliardi,<sup>56</sup> A. Gaz,<sup>56</sup> M. Margoni,<sup>56</sup> M. Morandin,<sup>56</sup> A. Pompili,<sup>56</sup> M. Posocco,<sup>56</sup> M. Rotondo,<sup>56</sup> F. Simonetto,<sup>56</sup> R. Stroili,<sup>56</sup> C. Voci,<sup>56</sup> E. Ben-Haim,<sup>57</sup> H. Briand,<sup>57</sup> G. Calderini,<sup>57</sup> J. Chauveau,<sup>57</sup> P. David,<sup>57</sup> L. Del Buono,<sup>57</sup> Ch. de la Vaissière,<sup>57</sup> O. Hamon,<sup>57</sup> Ph. Leruste,<sup>57</sup> J. Malclès,<sup>57</sup> J. Ocariz,<sup>57</sup> A. Perez,<sup>57</sup> L. Gladney,<sup>58</sup> M. Biasini,<sup>59</sup> R. Covarelli,<sup>59</sup> E. Manoni,<sup>59</sup> C. Angelini,<sup>60</sup> G. Batignani,<sup>60</sup> S. Bettarini,<sup>60</sup> M. Carpinelli,<sup>60</sup> R. Cenci,<sup>60</sup> A. Cervelli,<sup>60</sup> F. Forti,<sup>60</sup> M. A. Giorgi,<sup>60</sup> A. Lusiani,<sup>60</sup> G. Marchiori,<sup>60</sup> M. A. Mazur,<sup>60</sup> M. Morganti,<sup>60</sup> N. Neri,<sup>60</sup> E. Paoloni,<sup>60</sup> G. Rizzo,<sup>60</sup> J. J. Walsh,<sup>60</sup> M. Haire,<sup>61</sup> J. Biesiada,<sup>62</sup> P. Elmer,<sup>62</sup> Y. P. Lau,<sup>62</sup> C. Lu,<sup>62</sup> J. Olsen,<sup>62</sup> A. J. S. Smith,<sup>62</sup> A. V. Telnov,<sup>62</sup> E. Baracchini,<sup>63</sup> F. Bellini,<sup>63</sup> G. Cavoto,<sup>63</sup> A. D'Orazio,<sup>63</sup> D. del Re,<sup>63</sup> E. Di Marco,<sup>63</sup> R. Faccini,<sup>63</sup> F. Ferrarotto,<sup>63</sup> F. Ferroni,<sup>63</sup> M. Gaspero,<sup>63</sup> P. D. Jackson,<sup>63</sup> L. Li Gioi,<sup>63</sup> M. A. Mazzoni,<sup>63</sup> S. Morganti,<sup>63</sup> G. Piredda,<sup>63</sup> F. Polci,<sup>63</sup> F. Renga,<sup>63</sup> C. Voena,<sup>63</sup> M. Ebert,<sup>64</sup> T. Hartmann,<sup>64</sup> H. Schröder,<sup>64</sup> R. Waldi,<sup>64</sup> T. Adye,<sup>65</sup> G. Castelli,<sup>65</sup> B. Franek,<sup>65</sup> E. O. Olaiya,<sup>65</sup> S. Ricciardi,<sup>65</sup> W. Roethel,<sup>65</sup> F. F. Wilson,<sup>65</sup> R. Aleksan,<sup>66</sup> S. Emery,<sup>66</sup> M. Escalier,<sup>66</sup> A. Gaidot,<sup>66</sup> S. F. Ganzhur,<sup>66</sup> G. Hamel de Monchenault,<sup>66</sup> W. Kozanecki,<sup>66</sup> G. Vasseur,<sup>66</sup> Ch. Yèche,<sup>66</sup> M. Zito,<sup>66</sup> X. R. Chen,<sup>67</sup> H. Liu,<sup>67</sup> W. Park,<sup>67</sup> M. V. Purohit,<sup>67</sup> J. R. Wilson,<sup>67</sup> M. T. Allen,<sup>68</sup> D. Aston,<sup>68</sup> R. Bartoldus,<sup>68</sup> P. Bechtle,<sup>68</sup> N. Berger,<sup>68</sup> R. Claus,<sup>68</sup> J. P. Coleman,<sup>68</sup> M. R. Convery,<sup>68</sup> J. C. Dingfelder,<sup>68</sup> J. Dorfan,<sup>68</sup> G. P. Dubois-Felsmann,<sup>68</sup> W. Dunwoodie,<sup>68</sup> R. C. Field,<sup>68</sup> T. Glanzman,<sup>68</sup> S. J. Gowdy,<sup>68</sup> M. T. Graham,<sup>68</sup> P. Grenier,<sup>68</sup> C. Hast,<sup>68</sup> T. Hryn'ova,<sup>68</sup> W. R. Innes,<sup>68</sup> J. Kaminski,<sup>68</sup> M. H. Kelsey,<sup>68</sup> H. Kim,<sup>68</sup> P. Kim,<sup>68</sup> M. L. Kocian,<sup>68</sup> D. W. G. S. Leith,<sup>68</sup> S. Li,<sup>68</sup> S. Luitz,<sup>68</sup> V. Luth,<sup>68</sup> H. L. Lynch,<sup>68</sup> D. B. MacFarlane,<sup>68</sup> H. Marsiske,<sup>68</sup> R. Messner,<sup>68</sup> D. R. Muller,<sup>68</sup> C. P. O'Grady,<sup>68</sup> I. Ofte,<sup>68</sup> A. Perazzo,<sup>68</sup> M. Perl,<sup>68</sup> T. Pulliam,<sup>68</sup> B. N. Ratcliff,<sup>68</sup> A. Roodman,<sup>68</sup> A. A. Salnikov,<sup>68</sup> R. H. Schindler,<sup>68</sup> J. Schwiening,<sup>68</sup> A. Snyder,<sup>68</sup> J. Stelzer,<sup>68</sup> D. Su,<sup>68</sup> M. K. Sullivan,<sup>68</sup> K. Suzuki,<sup>68</sup> S. K. Swain,<sup>68</sup> J. M. Thompson,<sup>68</sup> J. Va'vra,<sup>68</sup> N. van Bakel,<sup>68</sup> A. P. Wagner,<sup>68</sup> M. Weaver,<sup>68</sup> W. J. Wisniewski,<sup>68</sup> M. Wittgen,<sup>68</sup> D. H. Wright,<sup>68</sup> A. K. Yarritu,<sup>68</sup> K. Yi,<sup>68</sup> C. C. Young,<sup>68</sup> P. R. Burchat,<sup>69</sup> A. J. Edwards,<sup>69</sup> S. A. Majewski,<sup>69</sup> B. A. Petersen,<sup>69</sup> L. Wilden,<sup>69</sup> S. Ahmed,<sup>70</sup> M. S. Alam,<sup>70</sup> R. Bula,<sup>70</sup> J. A. Ernst,<sup>70</sup> V. Jain,<sup>70</sup> B. Pan,<sup>70</sup> M. A. Saeed,<sup>70</sup> F. R. Wappler,<sup>70</sup> S. B. Zain,<sup>70</sup> W. Bugg,<sup>71</sup> M. Krishnamurthy,<sup>71</sup> S. M. Spanier,<sup>71</sup> R. Eckmann,<sup>72</sup> J. L. Ritchie,<sup>72</sup> A. M. Ruland,<sup>72</sup> C. J. Schilling,<sup>72</sup> R. F. Schwitters,<sup>72</sup> J. M. Izen,<sup>73</sup> X. C. Lou,<sup>73</sup> S. Ye,<sup>73</sup> F. Bianchi,<sup>74</sup> F. Gallo,<sup>74</sup> D. Gamba,<sup>74</sup> M. Pelliccioni,<sup>74</sup> M. Bomben,<sup>75</sup> L. Bosisio,<sup>75</sup> C. Cartaro,<sup>75</sup> F. Cossutti,<sup>75</sup> G. Della Ricca,<sup>75</sup> L. Lancieri,<sup>75</sup> L. Vitale,<sup>75</sup> V. Azzolini,<sup>76</sup> N. Lopez-March,<sup>76</sup> F. Martinez-Vidal,<sup>76</sup>,<sup>§</sup> D. A. Milanes,<sup>76</sup> A. Oyanguren,<sup>76</sup> J. Albert,<sup>77</sup> Sw. Banerjee,<sup>77</sup> B. Bhuyan,<sup>77</sup> K. Hamano,<sup>77</sup> R. Kowalewski,<sup>77</sup> I. M. Nugent,<sup>77</sup> J. M. Roney,<sup>77</sup> R. J. Sobie,<sup>77</sup> J. J. Back,<sup>78</sup> P. F. Harrison,<sup>78</sup> J. Ilic,<sup>78</sup> T. E. Latham,<sup>78</sup> G. B. Mohanty,<sup>78</sup> M. Pappagallo,<sup>78</sup>,<sup>¶</sup> H. R. Band,<sup>79</sup> X. Chen,<sup>79</sup> S. Dasu,<sup>79</sup> K. T. Flood,<sup>79</sup> J. J. Hollar,<sup>79</sup> P. E. Kutter,<sup>79</sup> Y. Pan,<sup>79</sup> M. Pierini,<sup>79</sup> R. Prepost,<sup>79</sup> S. L. Wu,<sup>79</sup> and H. Neal<sup>80</sup>

(The BABAR Collaboration)

<sup>1</sup>Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

<sup>2</sup>Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

<sup>3</sup>Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

<sup>4</sup>University of Bergen, Institute of Physics, N-5007 Bergen, Norway

<sup>5</sup>Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

<sup>6</sup>University of Birmingham, Birmingham, B15 2TT, United Kingdom

<sup>7</sup>Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

<sup>8</sup>University of Bristol, Bristol BS8 1TL, United Kingdom

<sup>9</sup>University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

<sup>10</sup>Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

<sup>11</sup>Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

<sup>12</sup>University of California at Irvine, Irvine, California 92697, USA

<sup>13</sup>University of California at Los Angeles, Los Angeles, California 90024, USA

<sup>14</sup>University of California at Riverside, Riverside, California 92521, USA

<sup>15</sup>University of California at San Diego, La Jolla, California 92093, USA

<sup>16</sup>University of California at Santa Barbara, Santa Barbara, California 93106, USA

<sup>17</sup>University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

<sup>18</sup>California Institute of Technology, Pasadena, California 91125, USA

<sup>19</sup>University of Cincinnati, Cincinnati, Ohio 45221, USA

<sup>20</sup>University of Colorado, Boulder, Colorado 80309, USA

<sup>21</sup>Colorado State University, Fort Collins, Colorado 80523, USA

- <sup>22</sup> Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
- <sup>23</sup> Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
- <sup>24</sup> Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
- <sup>25</sup> University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
- <sup>26</sup> Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
- <sup>27</sup> Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
- <sup>28</sup> Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
- <sup>29</sup> Harvard University, Cambridge, Massachusetts 02138, USA
- <sup>30</sup> Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
- <sup>31</sup> Imperial College London, London, SW7 2AZ, United Kingdom
- <sup>32</sup> University of Iowa, Iowa City, Iowa 52242, USA
- <sup>33</sup> Iowa State University, Ames, Iowa 50011-3160, USA
- <sup>34</sup> Johns Hopkins University, Baltimore, Maryland 21218, USA
- <sup>35</sup> Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
- <sup>36</sup> Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 ORSAY Cedex, France
- <sup>37</sup> Lawrence Livermore National Laboratory, Livermore, California 94550, USA
- <sup>38</sup> University of Liverpool, Liverpool L69 7ZE, United Kingdom
- <sup>39</sup> Queen Mary, University of London, E1 4NS, United Kingdom
- <sup>40</sup> University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
- <sup>41</sup> University of Louisville, Louisville, Kentucky 40292, USA
- <sup>42</sup> University of Manchester, Manchester M13 9PL, United Kingdom
- <sup>43</sup> University of Maryland, College Park, Maryland 20742, USA
- <sup>44</sup> University of Massachusetts, Amherst, Massachusetts 01003, USA
- <sup>45</sup> Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
- <sup>46</sup> McGill University, Montréal, Québec, Canada H3A 2T8
- <sup>47</sup> Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
- <sup>48</sup> University of Mississippi, University, Mississippi 38677, USA
- <sup>49</sup> Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
- <sup>50</sup> Mount Holyoke College, South Hadley, Massachusetts 01075, USA
- <sup>51</sup> Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
- <sup>52</sup> NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- <sup>53</sup> University of Notre Dame, Notre Dame, Indiana 46556, USA
- <sup>54</sup> Ohio State University, Columbus, Ohio 43210, USA
- <sup>55</sup> University of Oregon, Eugene, Oregon 97403, USA
- <sup>56</sup> Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
- <sup>57</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
- <sup>58</sup> University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
- <sup>59</sup> Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
- <sup>60</sup> Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
- <sup>61</sup> Prairie View A&M University, Prairie View, Texas 77446, USA
- <sup>62</sup> Princeton University, Princeton, New Jersey 08544, USA
- <sup>63</sup> Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
- <sup>64</sup> Universität Rostock, D-18051 Rostock, Germany
- <sup>65</sup> Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
- <sup>66</sup> DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
- <sup>67</sup> University of South Carolina, Columbia, South Carolina 29208, USA
- <sup>68</sup> Stanford Linear Accelerator Center, Stanford, California 94309, USA
- <sup>69</sup> Stanford University, Stanford, California 94305-4060, USA
- <sup>70</sup> State University of New York, Albany, New York 12222, USA
- <sup>71</sup> University of Tennessee, Knoxville, Tennessee 37996, USA
- <sup>72</sup> University of Texas at Austin, Austin, Texas 78712, USA
- <sup>73</sup> University of Texas at Dallas, Richardson, Texas 75083, USA
- <sup>74</sup> Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
- <sup>75</sup> Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
- <sup>76</sup> IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
- <sup>77</sup> University of Victoria, Victoria, British Columbia, Canada V8W 3P6
- <sup>78</sup> Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
- <sup>79</sup> University of Wisconsin, Madison, Wisconsin 53706, USA
- <sup>80</sup> Yale University, New Haven, Connecticut 06511, USA

(Dated: February 1, 2008)

We have searched for prompt production of  $\chi_{c1}, \chi_{c2}$  and  $X(3872)$  in continuum  $e^+e^-$  annihilations using a  $386 \text{ fb}^{-1}$  data sample collected around  $\sqrt{s} = 10.6 \text{ GeV}$  with the *BABAR* detector using the  $\gamma J/\psi$  decay mode. After accounting for the feed-down from  $\psi(2S) \rightarrow \gamma \chi_{c1,2}$ , no significant signal for prompt  $\chi_{c1,2}$  production is observed. We present improved upper limits on the cross-section, with the rest of the event consisting of more than two charged tracks, to be 77 fb for  $\chi_{c1}$  and 79 fb for  $\chi_{c2}$  with  $e^+e^-$  center-of-mass frame  $\chi_c$  momentum greater than 2.0 GeV at 90% confidence level. These limits are consistent with NRQCD predictions. We also set an upper limit on the prompt production of  $X(3872)$  through the decay  $X(3872) \rightarrow \gamma J/\psi$ .

PACS numbers: 13.66.Bc, 12.38.Qk, 12.38.Bx, 14.40.Gx

Charmonium production in  $e^+e^-$  annihilation provides opportunities to study both perturbative and non-perturbative effects in QCD and to search for new charmonium states [1, 2]. The prompt production of  $J/\psi$  and  $\psi(2S)$  in  $e^+e^-$  annihilation [3, 4] and of double-charmonium [5, 6] have been observed at  $B$ -factory experiments. These observations are surprising because the measured cross-sections are larger than non-relativistic QCD (NRQCD) calculations by up to an order of magnitude [1, 7].

In the NRQCD production mechanism, a heavy quarkonium ( $q\bar{q}$ ) state can be produced at short distances as a conventional color-singlet, or as a color-octet state, which then evolves into an observed quarkonium meson along with other light hadrons. With this color-octet mechanism, one may explain the enhancement for  $J/\psi$  production in  $e^+e^-$  annihilation [1]. The production of  $\chi_{c1,2}$  ( $\chi_c$ ) in  $e^+e^-$  annihilations is an excellent probe of color-octet contributions, which are more prominent in  $\chi_c$  production than in  $J/\psi$  production. This is because color-octet and color-singlet processes enter  $\chi_c$  production at the same order, and  $C$ -parity suppresses the process  $e^+e^- \rightarrow c\bar{c}gg$ , which dominates  $J/\psi$  production. Calculated cross-sections for prompt  $\chi_c$  production in  $e^+e^-$  annihilations are  $\sigma(e^+e^- \rightarrow \chi_{c1}X) = 85 \text{ fb}$  and  $\sigma(e^+e^- \rightarrow \chi_{c2}X) = 123 \text{ fb}$ , with  $e^+e^-$  center-of-mass (CM) frame  $J/\psi$  momentum  $p_{J/\psi}^* > 2.0 \text{ GeV}$ , and where  $X$  is one of  $q\bar{q}$ ,  $gg$  and  $g$  in the leading order processes and  $J/\psi$  is from  $\chi_c \rightarrow \gamma J/\psi$  decay [8]. More accurate measurements for  $\chi_c$  states will help to clarify the discrepancy between theoretical calculations and existing measurements, and may point to other methods and mechanisms in QCD to explain the differences.

Prompt production of charmonium mesons in  $e^+e^-$  annihilation has been searched for using either the reconstructed mass in an exclusive decay mode [3, 4] or the mass distribution of the system recoiling against the  $J/\psi$  or  $\psi(2S)$  [5, 6]. Although prompt production of  $\chi_{c0}$  has been observed, prompt production of the other  $\chi_c$  states,  $\chi_{c1}$  and  $\chi_{c2}$ , has not been observed.

In this paper, we present a search for prompt  $\chi_c$  production in continuum  $e^+e^-$  annihilation using the  $\gamma J/\psi$  ( $J/\psi \rightarrow \ell^+\ell^-$ ) decay mode, which is experimentally clean and is the dominant one in  $\chi_c$  decay. The current limits on prompt production of  $\chi_c$  are  $\sigma(e^+e^- \rightarrow \chi_{c1}X) < 350$

fb and  $\sigma(e^+e^- \rightarrow \chi_{c2}X) < 660 \text{ fb}$  with  $e^+e^-$  CM frame  $\chi_c$  momentum  $p_{\chi_c}^* > 2.0 \text{ GeV}$ , where  $X$  is the rest of the event [4]. Belle and *BABAR* recently observed an indication of the decay  $X(3872) \rightarrow \gamma J/\psi$  in  $B$  decays [9], and therefore we also search for prompt  $X(3872)$  production using the  $\gamma J/\psi$  decay mode in  $e^+e^-$  annihilation.

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  collider, where 9.0 GeV electrons and 3.1 GeV positrons are collided at a CM energy of 10.58 GeV, the mass of the  $\Upsilon(4S)$  resonance. The integrated luminosity ( $\mathcal{L}$ ) consists of  $349 \text{ fb}^{-1}$  ( $\mathcal{L}_{on}$ ) at the  $\Upsilon(4S)$  resonance and  $37 \text{ fb}^{-1}$  ( $\mathcal{L}_{off}$ ) at a center-of-mass energy 40 MeV below the resonance.

The *BABAR* detector is described elsewhere [10] and here we give only a brief overview. The momenta of charged particles are measured by the silicon vertex tracker, consisting of five layers of double-sided silicon strip sensors, and the central drift chamber (DCH) with 40 wire layers, both operating in a 1.5 T magnetic field of a solenoid. The tracking system covers 92% of the solid angle in the CM frame. An internally-reflecting ring-imaging Cherenkov detector (DIRC) with quartz bar radiators provides charged particle identification (PID). A CsI(Tl) electromagnetic calorimeter (EMC) is used to detect and identify photons and electrons, while muons are identified in the instrumented magnetic flux return system (IFR).

Electron candidates are identified by the ratio of the shower energy measured in the EMC to the track momentum measured in the DCH, the shower shape, the specific ionization energy loss in the DCH, and the Cherenkov angle measured by the DIRC. Muons are identified by the depth of penetration into the IFR, the IFR cluster geometry, and the energy deposited in the EMC. Photon candidates are identified by EMC clusters that have a shape consistent with an electromagnetic shower and are not associated with a charged track.

We use a Monte Carlo (MC) simulation of the *BABAR* detector based on GEANT4 [11] to validate the analysis procedure, to evaluate signal detection efficiencies, to model probability density functions (PDFs), and to estimate background contributions. We use samples of  $e^+e^- \rightarrow \chi_{c1,2} + J/\psi$  or  $\psi(2S)$  MC events to determine the selection criteria. To estimate the signal re-

construction efficiencies and PDFs, we use single  $\chi_c$  MC samples decaying to  $\gamma J/\psi$  with  $J/\psi \rightarrow e^+e^-$  or  $J/\psi \rightarrow \mu^+\mu^-$ , which are generated with flat distributions in  $p^*$  (CM frame  $\chi_c$  momentum) and  $\cos\theta^*$  (cosine of the polar angle of the  $\chi_c$  momentum to the beam axis in the CM frame). To understand combinatorial background, we use MC generated  $e^+e^- \rightarrow \eta_c, \chi_{c0}$ , or  $\eta_c(2S)$  events produced in association with either  $J/\psi$  or  $\psi(2S)$  mesons.  $B\bar{B}$  generic and initial state radiation (ISR)  $\psi(2S)$  ( $e^+e^- \rightarrow \gamma\psi(2S)$ ) MC events are used to estimate background contamination. The  $\chi_c$  candidates from  $B$  decay are used as a control data sample to correct for differences in the photon energy measurements between MC simulation and data.

Charged particles are required to have a point of closest approach to the beam spot of less than 10 cm along the beam axis and less than 1.5 cm in the plane transverse to the beam. The  $J/\psi$  mesons are reconstructed in the dilepton channel using two oppositely-charged tracks identified as electrons or muons. An algorithm to recover the energy loss due to bremsstrahlung is applied to electron candidates. The invariant mass of the reconstructed  $J/\psi$  is required to be within the range [3.07, 3.13] GeV for the  $\mu^+\mu^-$  channel and [3.05, 3.13] GeV for the  $e^+e^-$  channel. The asymmetric selection in the  $e^+e^-$  channel is due to initial and final state radiation. The  $J/\psi$  candidate is subjected to a vertex constrained fit and is combined with a photon candidate that satisfies standard reconstruction quality criteria as described below. Multiple signal candidates in the event are allowed.

The photon candidates are EMC clusters in the angular region  $0.41 < \theta < 2.41$  radians where  $\theta$  is the polar angle with respect to the beam axis in the laboratory frame. The lateral energy distribution ( $LAT$ ) [12] measures the transverse energy profile of a cluster; requiring this to be less than 0.5 suppresses clusters due to both electronic noise and hadronic interactions. The azimuthal asymmetry of the energy deposition in a cluster is measured by the  $A_{42}$  Zernike moment [13]. Requiring  $A_{42}$  less than 0.1 further rejects clusters from hadronic interactions. In addition, the angular separation between the direction of the candidate and of any charged track in the event should be at least  $9^\circ$  in the laboratory frame (split-off rejection). The clusters satisfying these criteria come mostly from  $\pi^0$  decay. We reject photon candidates that, when combined with any other photon, produce a mass between 114 MeV and 146 MeV ( $\pi^0$  veto). The partner photon must have energy greater than 30 MeV and  $LAT < 0.8$  without any requirement on  $A_{42}$  and split-off rejection.

Backgrounds arise from combinatorial background in  $B$  decays and continuum events, and decays of  $\psi(2S)$  mesons produced either promptly or in ISR events. To suppress  $B$ -background contributions, we require  $p_{\chi_c}^* > 2.0$  GeV and  $p_{J/\psi}^* > 2.0$  GeV. For the  $\chi_c$  control sample, we require  $p_{\chi_c}^* < 1.7$  GeV and  $p_{J/\psi}^* < 2.0$  GeV. The

combinatorial background for  $J/\psi$  candidates in continuum events is reduced by requiring  $|\cos\theta_H^{J/\psi}| < 0.9$  [6], where  $\theta_H^{J/\psi}$  is the  $J/\psi$  helicity angle, measured in the rest frame of the  $J/\psi$ , between the positively charged lepton daughter and the  $\gamma J/\psi$  system.

The backgrounds from prompt  $\psi(2S)$  radiative decay to  $\gamma\chi_c$  are indistinguishable from the signal. The estimated contribution from prompt  $\psi(2S)$  production will be subtracted from the measured cross-sections.

Substantial backgrounds are due to ISR production of  $\psi(2S)$  decaying to  $\gamma\chi_c$ , which produces low multiplicity and a jet-like event shape. To suppress such backgrounds, the ratio  $R_2$  of second and zeroth Fox-Wolfram moments of the event [14] is required to be less than 0.8 and the number of charged particles in the event is required to be at least five ( $N_{ch}$  cut). We estimate the possible contributions from ISR production using MC samples and subtract them from the signal yield. Two-photon background contributions are estimated to be negligible with all selection criteria applied.

The helicity angle of the  $\gamma J/\psi$  system ( $\theta_H$ ) is the angle, measured in the rest frame of the  $\gamma J/\psi$  system, between the momentum of the  $J/\psi$  and the momentum of the  $e^+e^-$  center-of-mass in the laboratory frame. The  $J/\psi$  mesons from combinatorial background tend to be along the direction of the boost vector which makes  $\cos\theta_H$  close to unity whereas the distribution of signal events is flat. We optimize the  $\cos\theta_H$  cut using MC samples by maximizing the figure of merit  $N_{sig}^2/(N_{cont} + N_{B\bar{B}})$ , where  $N_{sig}$ ,  $N_{cont}$  and  $N_{B\bar{B}}$  are the numbers of events from signal, continuum, and  $B\bar{B}$  background expected in the data sample respectively. The scale of  $N_{sig}$  is not sensitive to the optimized cut. For  $N_{cont}$  we use the yield from off-resonance data multiplied by  $(\mathcal{L}_{on} + \mathcal{L}_{off})/\mathcal{L}_{off}$ . The optimized cut is found to be  $\cos\theta_H < 0.4$ . The same cut is applied for the  $X(3872)$  search which has similar kinematics.

We extract the signal yield using an unbinned maximum likelihood (UML) fit (nominal fit) for the distribution of  $\Delta M$ , the mass difference between the signal  $\chi_c$  or  $X(3872)$  candidate and the daughter  $J/\psi$  candidate. We use a  $\Delta M$  range [0.25, 0.60] GeV for the  $\chi_c$  searches and [0.60, 0.95] GeV for the  $X(3872)$  search in the nominal fit. To estimate the systematic uncertainty, we use [0.25, 0.35] GeV and [0.50, 0.60] GeV as sideband regions and [0.35, 0.50] GeV as the core signal region for the  $\chi_c$  states.

The  $\Delta M$  distribution for signal candidates is described by a Crystal Ball Line shape (CBL) which is a Gaussian (described by the peak value  $\Delta M_0$  and resolution  $\sigma_{\Delta M}$ ) with a power law tail  $1/(\Delta M_0 - \Delta M + \text{const})^n$ , at a value of  $\Delta M_0 - \alpha \cdot \sigma_{\Delta M}$ . We use different PDFs for  $\chi_{c1}$ ,  $\chi_{c2}$ , and  $X(3872)$ , averaged over the  $e^+e^-$  and  $\mu^+\mu^-$  modes. The parameter values used in the CBL are determined using MC simulation and are then fixed in the nominal

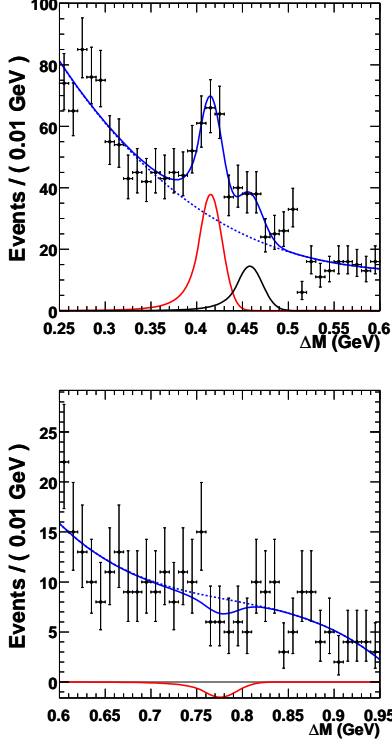


FIG. 1: (color online) Nominal fit result for the  $\chi_c$  search (top) and the  $X(3872)$  search (bottom) from the  $386 \text{ fb}^{-1}$  data sample ( $p^* > 2.0 \text{ GeV}$ ). The points represent the data, the dashed lines are background PDFs, the solid lines below the points are signal PDFs, and the solid lines on the points are the total PDFs.

fit. The resolution  $\sigma_{\Delta M}$  is 14.0 MeV, 15.3 MeV and 20.5 MeV for  $\chi_{c1}$ ,  $\chi_{c2}$ , and  $X(3872)$  respectively and these are scaled by  $\beta$ , a scale factor for the  $\Delta M$  resolution. The mean  $\Delta M_0$  for each of  $\chi_{c1}$ ,  $\chi_{c2}$ , and  $X(3872)$  is given by the known mass shifted by  $\delta$ , an offset of the PDF in  $\Delta M$ . The difference of the  $\chi_{c1}$  and  $\chi_{c2}$  masses is constrained to the known value 45.5 MeV [15]. The  $\beta$  and  $\delta$  parameters are determined as  $\beta = 0.89 \pm 0.03$  and  $\delta = (2.7 \pm 0.4) \text{ MeV}$  using a control data sample of  $\chi_c$  mesons from  $B$  decay and fixed in the nominal fit. The background line shape is described by a third-order Chebyshev polynomial with free coefficients.

The results for the nominal fit are presented in Fig. 1. For the  $\chi_{c1}$  and  $\chi_{c2}$  searches, we analyze 1417 events after all selection criteria. The number of  $\chi_{c1}$  candidates is  $134 \pm 23$  and the number of  $\chi_{c2}$  candidates is  $56 \pm 19$ . For the  $X(3872)$  search, we find  $N_{X(3872)} = -8 \pm 11$  from 293 events.

The ISR  $\psi(2S)$  backgrounds are estimated using MC samples to be 9.4 events for  $\chi_{c1}$  and 5.1 events for  $\chi_{c2}$ . Subtracting these from the fitted yields we find  $N_{\chi_{c1}} = 125 \pm 23$  and  $N_{\chi_{c2}} = 51 \pm 19$ , which we attribute to the sum of prompt  $\chi_c$  production and feed-down from prompt  $\psi(2S)$  production.

To estimate the signal detection efficiency  $\epsilon$ , we decompose it into three factors: efficiencies of reconstruction ( $\epsilon_r$ ),  $\pi^0$  veto ( $\epsilon_v$ ) and split-off rejection ( $\epsilon_s$ ). The efficiency becomes smaller in low  $p^*$  bins and high  $\cos\theta^*$  bins owing to the  $p_{J/\psi}^* > 2.0 \text{ GeV}$  requirement and lower detector coverage near the endcap region. To get an estimate of  $\epsilon_r$ , we divide the region  $2.0 < p^* < 5.0 \text{ GeV}$  into 6 bins and  $-1.0 < \cos\theta^* < 1.0$  into 5 bins. We correct using the formula  $\epsilon_r = w_i^{p^*} \epsilon_{ij} w_j^{\cos\theta^*}$  where  $w_i^{p^*}$  and  $w_j^{\cos\theta^*}$  are weights and  $\epsilon_{ij}$  is an efficiency matrix ( $i=1,6$ ;  $j=1,5$ ), averaged over the  $e^+e^-$  and  $\mu^+\mu^-$  modes using single particle MC samples. The weights are defined by

$$w_i = \frac{N_i^{p^*} / \epsilon_i^{p^*}}{\sum_{k=1}^6 N_k^{p^*} / \epsilon_k^{p^*}}, \quad w_j = \frac{N_j^{\cos\theta^*} / \epsilon_j^{\cos\theta^*}}{\sum_{k=1}^5 N_k^{\cos\theta^*} / \epsilon_k^{\cos\theta^*}},$$

where  $\epsilon_i^{p^*}$  and  $\epsilon_j^{\cos\theta^*}$  are efficiencies in bins of  $p^*$  and  $\cos\theta^*$ , determined from the single  $\chi_c$  MC samples, and  $N_i^{p^*}$  and  $N_j^{\cos\theta^*}$  are the yields in each bin, extracted from the binned fit to the data sample. For the  $X(3872)$  search, we use the averaged efficiency when the weights for  $\chi_{c1}$  and  $\chi_{c2}$  are used, because of the limited statistics for the number of  $X(3872)$  candidates. The  $\epsilon_{ij}$  values are determined from the single  $X(3872)$  MC sample. With these corrections, the  $\epsilon_r$  values are 10.1%, 9.3%, and 8.4% for  $\chi_{c1}$ ,  $\chi_{c2}$ , and  $X(3872)$ , respectively.

To estimate  $\epsilon_v$  and  $\epsilon_s$ , we need to have knowledge of the efficiency as a function of photon ( $N_\gamma$ ) or charged track multiplicity ( $N_{ch}$ ), and the  $N_\gamma$  or  $N_{ch}$  fractional distribution of signal events, because  $\epsilon_v$  and  $\epsilon_s$  are strongly dependent on the number of photons or charged tracks in the event. We estimate efficiencies for each  $N_\gamma$  and  $N_{ch}$  bin using signal MC simulation corrected by the data-to-MC difference using  $\chi_c$  candidates from  $B$  decays. The distributions of  $N_\gamma$  and  $N_{ch}$  for signal events are estimated from the sideband-subtracted data sample. The  $N_\gamma$  distribution ranges from 1 to 18 and the  $N_{ch}$  distribution ranges from 5 to 14. We estimate  $\epsilon_v = 0.80$  and  $\epsilon_s = 0.96$  from an average calculated by the following formula:

$$\epsilon = \frac{\sum_i N_{pi} \cdot \epsilon(N_i)}{\sum_j N_{pj}} = \frac{\sum_i N_{oi}}{\sum_j N_{pj}}$$

where  $N_{pi}$  stands for the number of photons or charged tracks produced in the  $i$ th bin,  $N_{oi}$  for the number of photons or charged tracks observed in the  $i$ th bin,  $N_{pi} = N_{oi} / \epsilon(N_i)$ , and  $\epsilon(N_i)$  is the efficiency of the  $i$ th bin in the distribution of  $N_\gamma$  or  $N_{ch}$ . For the  $X(3872)$  search, we use the same  $\epsilon_v$  and  $\epsilon_s$  as for the  $\chi_c$ . The total efficiency  $\epsilon$  is the product  $\epsilon_r \cdot \epsilon_v \cdot \epsilon_s$  and is estimated to be 7.7%, 7.1% and 6.4%, respectively, for the  $\chi_{c1}$ ,  $\chi_{c2}$ , and  $X(3872)$ .

TABLE I: Systematic uncertainties (quoted in %) on  $\sigma_{N_{ch}>2}$  defined in the text.

	$\chi_{c1}$	$\chi_{c2}$	$X(3872)$
$p^*/\cos\theta^*$ correction	13.3	26.5	34.9
Track efficiency	0.5	0.5	0.5
Charged PID	7.2	7.2	7.2
Photon PID	1.8	1.8	1.8
$\pi^0$ veto efficiency ( $\epsilon_v$ )	2.3	2.3	2.3
Split-Off rejection efficiency ( $\epsilon_s$ )	0.4	0.4	0.4
PDF	3.5	11.2	15.1
ISR Background	3.8	5.0	—
$\prod \mathcal{B}_i$	5.4	5.0	0.7
Total	17.1	30.6	38.8

The sources of systematic uncertainty are summarized in Table I. The dominant uncertainty is from the reconstruction efficiency ( $\epsilon_r$ ) correction from the  $p^*$  and  $\cos\theta^*$  distributions. For the  $\chi_c$  search, we assign the systematic uncertainty as the r.m.s. spread of 10,000 simulated experiments (each experiment gives one  $\epsilon_r$  value) with weights generated according to the central values and errors from the  $p^*$  and  $\cos\theta^*$  binned fit results. For the  $X(3872)$  search, we adopt a conservative approach. We calculate separately the r.m.s. values corresponding to the binned fit results for  $\chi_{c1}$  and  $\chi_{c2}$ , and assign the sum of r.m.s. values as the systematic uncertainty for the  $X(3872)$  reconstruction efficiency.

The error from the PDF modeling is estimated by a quadratic sum over the changes in the yield from an alternative background line shape  $e^{-[p_0+p_1(\Delta M)+p_2(\Delta M)^2]}$ , and  $\pm 1$  standard deviation of the uncertainties in the measured  $\delta$  and  $\beta$  in the  $\chi_c$  control sample from  $B$  decay. We take the data-to-MC difference in track reconstruction efficiency as a source of systematic uncertainty. To estimate systematic uncertainties in charged PID efficiencies, we assign the difference when taking  $\pm 1$  standard deviation of each error depending on momentum and azimuthal angle of tracks measured using control samples. The systematic uncertainty of photon identification is estimated by comparing data with MC simulations of  $\tau^+ \rightarrow \pi^+ \nu$  and  $\tau^+ \rightarrow \rho(\pi^+ \pi^0) \nu$  samples. We assign half of the ISR  $\psi(2S)$  background estimate as systematic uncertainty for the  $\chi_c$  search. The uncertainty of the ISR background is neglected for the  $X(3872)$  search. The  $\prod \mathcal{B}_i$  is a product of sub-decay mode branching fractions, that is  $\mathcal{B}(\chi_c \rightarrow \gamma J/\psi) \cdot [\mathcal{B}(J/\psi \rightarrow e^+ e^-) + \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)]$ . The systematic error related to  $\prod \mathcal{B}_i$  is estimated from the reference values [15]. The systematic uncertainties from  $\epsilon_v$  and  $\epsilon_s$  evaluations are estimated by a quadratic sum over the deviations in two cases: when the data-to-MC correction is not used and when  $N_\gamma$  and  $N_{ch}$  distributions are taken without sideband subtraction to see the effect of backgrounds on the distribution.

Table II summarizes the measurements and all the quantities we need to calculate  $\sigma_{N_{ch}>2}$ , that is the cross-section of prompt  $\chi_c$  or  $X(3872)$  production ( $\sigma(e^+ e^- \rightarrow$

$c\bar{c}X$ )) times the probability of the rest of the event ( $X$ ) having more than two charged tracks,  $\mathcal{P}_{N_{ch}>2}$ . The result  $\sigma_{N_{ch}>2}$  is derived from the formula  $N_{sg} = \mathcal{L} \cdot \epsilon \cdot \sigma_{N_{ch}>2} \cdot \prod \mathcal{B}_i$  where  $N_{sg}$  is the number of  $\chi_c$  or  $X(3872)$  candidates from  $e^+ e^-$  annihilation. In the case of  $\chi_c$ ,  $\sigma_{N_{ch}>2}$  includes the prompt  $\psi(2S)$  feed-down contribution. For the  $X(3872)$ , we measure the product  $\sigma_{N_{ch}>2} \cdot \mathcal{B}(X(3872) \rightarrow \gamma J/\psi)$  because the  $X(3872) \rightarrow \gamma J/\psi$  BF is unknown.

TABLE II: Signal yield  $N_{sg}$  from the nominal fit after subtracting the ISR  $\psi(2S)$  estimate; signal detection efficiency ( $\epsilon = \epsilon_r \cdot \epsilon_v \cdot \epsilon_s$ ); product of sub-decay mode BF's ( $\prod \mathcal{B}_i$ ); integrated on- and off-resonance luminosity ( $\mathcal{L}$ );  $\sigma_{N_{ch}>2}$  (defined in the text) and its upper limit including systematic uncertainties;  $\sigma_{N_{ch}>2}^{prompt}$  ( $\sigma_{N_{ch}>2}$  for the prompt production) and its upper limit including systematic uncertainties. Upper limits are at the 90% C.L. Note that  $\sigma_{N_{ch}>2}$  for  $X(3872)$  denotes  $\sigma_{N_{ch}>2} \cdot \mathcal{B}(X(3872) \rightarrow \gamma J/\psi)$ .

	$\chi_{c1}$	$\chi_{c2}$	$X(3872)$
$N_{sg}$	125 $\pm$ 23	51 $\pm$ 19 ( < 75 )	-8.0 $\pm$ 11 ( < 15 )
$\epsilon$ (%)	7.7	7.1	6.4
$\prod \mathcal{B}_i$ (%)	4.2	2.4	11.9
$\mathcal{L}$ (fb $^{-1}$ )	386	386	386
$\sigma_{N_{ch}>2}$ (fb)	99 $\pm$ 18 $\pm$ 17	78 $\pm$ 28 $\pm$ 24 < 125	-3 $\pm$ 4 $\pm$ 1 < 5
$\sigma_{N_{ch}>2}^{prompt}$ (fb)	41 $\pm$ 18 $\pm$ 21	23 $\pm$ 28 $\pm$ 26 < 77	-3 $\pm$ 4 $\pm$ 1 < 79 < 5

For prompt  $\chi_c$  production, it is necessary to subtract prompt  $\psi(2S)$  feed-down to  $\chi_c$ . The contribution of prompt  $\psi(2S)$  production is estimated to be  $(58 \pm 12)$  fb for  $\chi_{c1}$  and  $(54 \pm 11)$  fb for  $\chi_{c2}$  using  $\sigma(e^+ e^- \rightarrow \psi(2S)X) = (0.67 \pm 0.13)$  pb for  $p^* > 2.0$  GeV [4] and the  $\psi(2S) \rightarrow \gamma \chi_c$  BF [15]. The errors are included as systematic uncertainties in the prompt  $\chi_c$  production cross-section. Feed-down from other  $\psi(2S)$  decay modes with photons is checked using MC simulation:  $J/\psi \pi^0 \pi^0$ ,  $J/\psi \eta(\gamma \gamma)$ ,  $J/\psi \eta(\gamma \pi^+ \pi^-)$ ,  $J/\psi \eta(\pi^+ \pi^- \pi^0)$ , and  $J/\psi \eta(\pi^0 \pi^0 \pi^0)$ . No background from these decays is seen in the MC simulation. The resultant cross-sections,  $\sigma_{N_{ch}>2}^{prompt}$ , for  $\chi_c$  production are shown in Table II.

Our measurements use an additional kinematic cut  $p_{\chi_c}^* > 2.0$  GeV which has little effect on the cross-section because leading-order contributions are from two-body  $e^+ e^-$  annihilation processes. To compare these results with the theoretical predictions in Ref. [8], the value of  $\mathcal{P}_{N_{ch}>2}$  should be estimated correctly. Nevertheless, our upper limits are comparable with the NRQCD cross-section predictions.

In summary, we have searched for prompt production of  $\chi_{c1}$  and  $\chi_{c2}$  in  $e^+ e^-$  annihilation near  $\sqrt{s} = 10.6$  GeV. We observe candidates for these  $\chi_c$  states, but the measured cross-sections are compatible, within statistics,

with the expected contributions of  $\chi_c$  feed-down from prompt  $\psi(2S)$  production. The 90% confidence level upper limits on  $\sigma_{N_{ch}>2}^{prompt}$  are 77 fb for  $\chi_{c1}$  and 79 fb for  $\chi_{c2}$  with  $p_{\chi_c}^* > 2.0$  GeV. We find no evidence for prompt  $X(3872)$  production via the decay  $X(3872) \rightarrow \gamma J/\psi$ . We set the 90% confidence level upper limit on  $\sigma_{N_{ch}>2} \cdot \mathcal{B}(X(3872) \rightarrow \gamma J/\psi)$  to be 5 fb. The upper limits presented on prompt  $\chi_c$  production are significant improvements on the previously reported results [4]. These limits are comparable to the theoretical cross-section predictions of Ref. [8]. Upper limits on prompt production of  $\chi_c$  in comparison with  $J/\psi$  and  $\psi(2S)$  prompt production [3, 4], can be used to further our understanding of the charmonium prompt production mechanism [1, 2, 8].

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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<sup>†</sup> Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

<sup>‡</sup> Also with Università della Basilicata, Potenza, Italy

<sup>§</sup> Also with Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

<sup>¶</sup> Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom

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